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Comparison and Evaluation of Operational Mesoscale MM5 and BFM Over WSMR

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Statistical parameters such as mean difference, absolute difference, root mean square error, and root mean square vector error are calculated between forecast data and observed data for both models. Surface meteorological parameters, temperature, relative humidity, horizontal wind vector components, and wind speed are used for the present study.

Statistics for individual stations as well as all the SAMS stations covering the 42-day period are analyzed.

This study shows that both models predicted the surface temperature fields well. MM5 tends to over predict relative humidity, whereas BFM tends to under predict it. Both models tend to under predict wind speed, but the BFM calculation produces smaller wind speeds than MM5. The BFM produced a better vector wind than did MM5.

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Preface

This report describes the results of statistical comparisons of surface meteorological parameters forecasted by both the Fifth-Generation National Center for Atmospheric Research/Penn State Mesoscale Model (MM5) and the U.S. Army Battlescale Forecast Model (BFM) to the Surface Atmosphere Measuring System data at the White Sands Missile Range (WSMR), covering the period of April and May 1999.

MM5 is now employed operationally at the WSMR weather station for short-range (up to 24 hr) forecasting. The BFM, developed at the U.S. Army Research Laboratory, is a major part of the U.S. Army Integrated Meteorological System.

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Executive Summary

Forecast data of both Fifth-Generation Mesoscale Model (MM5) and the Battlescale Forecast Model (BFM) were statistically compared with the Surface Atmosphere Measuring System (SAMS) data at the White Sands Missile Range covering the period of April and May 1999. Archived forecast data from MM5 and SAMS, and output data from the BFM are used for this study.

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This study shows that both models predicted the surface temperature fields well. MM5 tends to over-predict relative humidity, whereas BFM tends to under-predict it. Both models tend to under-predict wind speed, but the BFM calculation produces smaller wind speeds than MM5. The BFM produced a better vector wind than MM5 did.

1. Introduction

The White Sands Missile Range (WSMR) weather station, "C" station, is now using the Fifth-Generation National Center of Atmospheric Research (NCAR)/Penn State Mesoscale Model (MM5) as a tool for short-range (24 h) weather forecast. MM5 is a limited area, nonhydrostatic, terrain following, sigma-coordinate model to predict mesoscale and regional-scale atmospheric circulations. Details about the model can be found on its internet MM5 home web page: http://www.ucar.edu/mm5/mm5-home.html. Forecasts are routinely made twice a day initialized at 0000 and 1200 UTC over the model domain covering WSMR and the surrounding area. These forecasts and the Surface Atmosphere Measuring System (SAMS) data are being archived by the "C" station. [1]

The Battlescale Forecast Model (BFM), developed at the U. S. Army Research Laboratory (ARL), is used to make short-range forecasts of atmospheric conditions in the Integrated Meteorology System (IMETS) and the Computer Assisted Artillery Meteorology (CAAM) system. The BFM is designed to forecast atmospheric conditions over a battlescale area (500 x 500 km or less). The BFM is globally relocatable except for high latitude regions and has been used for different parts of the world. Detail of the BFM is described by T. Henmi and R. Dumais. [2,3,4]

Archived data of MM5, SAMS, and the BFM forecast over the WSMR domain provide excellent data sets with which to evaluate and compare MM5 and BFM. There have been several reports of mesoscale model comparison studies, as reviewed in the next section, but the past studies were based on the results of a limited number of cases. The present study is based on 42, 24-h forecast calculations of MM5 and BFM compared with observational results.

1.1 Purpose

The purpose of this report is to present the results of this study. A review of preceding comparison studies of mesoscale models is given in section 2. In section 3, archived MM5 and SAMS data along with BFM applications to WSMR are discussed. Comparison methods are introduced in section 4, while the results of this study are shown in section 5. Section 6 summarizes the present study.

2. Review of the Mesoscale Model Comparison Studies

The U.S. Army Atmospheric Science Laboratory (early designation of the Battlefield Environment Division, Information Science & Technology, ARL) sponsored a Mesoscale Model Comparison workshop in 1992. Two sets of 24-h observation data obtained in project WIND were used to compare model simulation results. The model domain was an area of 200 x 200 km (41 x 41 horizontal grid points with grid spacing of 5 km) located in Northern California. Four different models participated in the workshop:

1. the numerical simulation model for Flow Over Irregular Terrain with Natural and Anthropogenic Heat sources (FITNAH) developed by Gross,

2. the Fourth-Generation NCAR/Penn State Mesoscale Model (MM4) operated by the group at Tel Aviv University,

3. the Colorado State University (CSU) Regional Atmospheric Modeling System (RAMS), and

4. the Higher Order Turbulence Model for Atmospheric Circulation (HOTMAC). [4,5,6,7,8,9,10,11]

Of these models, FITNAH was the only nonhydrostatic and the other three models were hydrostatic. The results of the workshop were published, and statistical evaluations of simulation results by these four models were presented by Gross. In general, for the summertime data set, all the models were able to reproduce the diurnally-forced upslope and downslope winds, including their times of onset. All models were successful in producing temperature changes. However, for the wintertime data set, all four models failed to reproduce the range of observed wind speeds due to an inability to resolve the rapid changes associated with the frontal passage. However, all the models reproduced the narrow range of observed wind directions. [12, 13]

Cox, et al performed the intercomparison study of four mesoscale models by applying them to five different theater scale regions. A theater scale region is a rectangular region of 2800 to 6000 km on a side. In their study, the model simulations were made over the five different climatological

areas of 3220 x 3220 km (71 x 71 horizontal grid points with 46 km grid spacing). [14]

The five areas were:

1. Continental United States,
2. Alaska region including parts of Siberia and Canada,
3. Central American region,
4. Korean region including parts of China and Japan, and
5. Middle East region.

The models studied were:

1. Fifth Generation NCAR/Penn State Mesoscale Model (MM5),

2. CSU RAMS (nonhydrostatic version),

3. Navy Operational Regional Prediction System Version 6 (NORAPS6), and

4. the U.S. Air Force mesoscale model, the Relocatable Window Model (RWM)

The versions of MM5 and RAMS used in the study are nonhydrostatic. NORAPS6 and RWM are hydrostatic models. Initial conditions and time-dependent boundary conditions were provided by the U.S. Air Force's Global Spectral Model at a 2.5 E grid resolution. Surface and rawinsonde data, and the National Meteorological Center (NMC) global analysis 2.5 E gridded data fields were used to compare the model simulation results. The simulation calculations were performed for three, three-day periods in five regions, and two independent 36-h forecasts were made during each three-day period. Comparison of model simulation results with observational data indicated that RAMS forecasts were statistically closer to the observed values most often, with MM5 following next.

3. MM5, SAMS Data, and BFM Forecast Data

3.1 MM5 Data

The WSMR MM5 forecasts are done on three nests :

Grid	Grid numbers	Grid distance (km)
1	84 x 98	30
2	67 x 71	10
3	61 x 61	3.3

and 31 vertical layers are used. The vertical σ-coordinate used in MM5 is defined as:

$$\sigma = \frac{p_0 - p_t}{p_s - p_t} \quad (1)$$

where

p_s and p_t are the surface and top pressures, respectively, of the reference state and are independent of time

p_0 is the reference state pressure and dependent on height only. [15]

The initial and time dependent lateral-boundary values, for model forecast calculations, are provided by the forecast data of Eta model run by the National Center for Environmental Prediction (NCEP). The center of all the model domain is located at 33.0° N and 106.0° W.

The grid 3 domain is located to cover WSMR. Grid 3 data were interpolated to the locations of the SAMS sites and the interpolated data. Forecast data of MM5 (PSAMS) are archived. PSAMS data are composed of hourly forecasts over two 12-h forecast periods initialized at 0000 and 1200 UTC that includes temperature and relative humidity values at the 2 m level, wind speed, and direction at the 10 m level. Hourly data are displayed at 1 to 11, and 13 to 23 UTC. Few or no data at 0, 12, and 24 UTC are given in data set. The surface data were obtained by extrapolating the data at the lowest level of model (about 40 m above ground surface) to the surface level, using the similarity theory

relationships. These surface data are statistically compared to the SAMS data. [16,17]

3.2 SAMS Data

The locations of the WSMR SAMS sites are shown in figure 1. Table 1 displays the elevation, and latitudinal and longitudinal locations. Both figure 1 and table 1 were obtained from the internet home page of WSMR Weather Station (http://weather.wsmr.army.com). In the table, the stations in bold characters, which are located within the BFM model domain, are used for the present study.

Figure 1. Map showing the locations of WSMR SAMS.

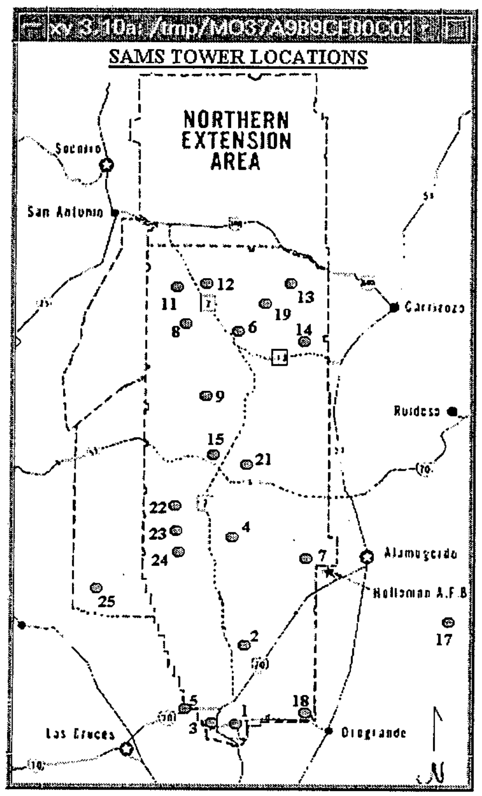


Table 1. Elevation, latitudes and longitudes of WSMR SAMS

Station Number	Elevation (Feet)	Latitude (° N)	Longitude (° W)	Station Name
1	**4005**	**32.36**	**106.38**	**'C station'**
2	**3953**	**32.66**	**106.40**	**'Apache Site'**
3	**4272**	**32.37**	**106.49**	**'WSMR Post'**
4	**3911**	**32.90**	**106.41**	**'Northrup Strip'**
5	**5901**	**32.40**	**106.50**	**'San Augustine Pass'**
6	**5356**	**33.50**	**106.54**	**'Mockingbird Gap'**
7	**4058**	**32.90**	**106.13**	**'Ninninger Site'**
8	**4745**	**33.47**	**106.58**	**'Zumwalt Track'**
9	**8941**	**33.30**	**106.53**	**'Salinas Peak'**
11	4877	33.80	106.68	'LBTS'
12	4785	33.80	106.59	'Zurf Site'
13	5290	33.74	106.43	'4 Mile Site'
14	**4530**	**33.50**	**106.21**	**'Oscura Range Camp'**
15	**4057**	**33.17**	**106.49**	**'Jallen Site'**
17	**9169**	**32.79**	**105.82**	**'Sacramento Peak'**
18	**4180**	**32.40**	**106.15**	**'Orogrande Gate'**
19	4917	33.63	106.48	'Duquette'

Note Stations in bold characters are used for the present comparison studies.

Table 1. Elevation, latitudes and longitudes of WSMR SAMS (continued)

Station Number	Elevation (Feet)	Latitude (° N)	Longitude (° W)	Station Name
21	**4031**	**33.17**	**106.34**	**'ABC 1'**
22	**4600**	**32.63**	**106.51**	**'Ash Canyon'**
23	**4500**	**32.74**	**106.51**	**'San Andreas'**
24	**4700**	**32.96**	**106.56**	**'Hembrillo'**
25	**4780**	**32.79**	**106.78**	**'Space Port'**
26	4002	32.38	106.28	'Radar 595'
27	4078	32.09	106.16	'Radar 613'
28	4050	32.06	106.18	'Radar 455'
29	4666	33.56	106.65	'Radar 940'
30	3978	32.88	106.50	'Radar 449'
31	4255	32.80	106.50	'Radar 551'

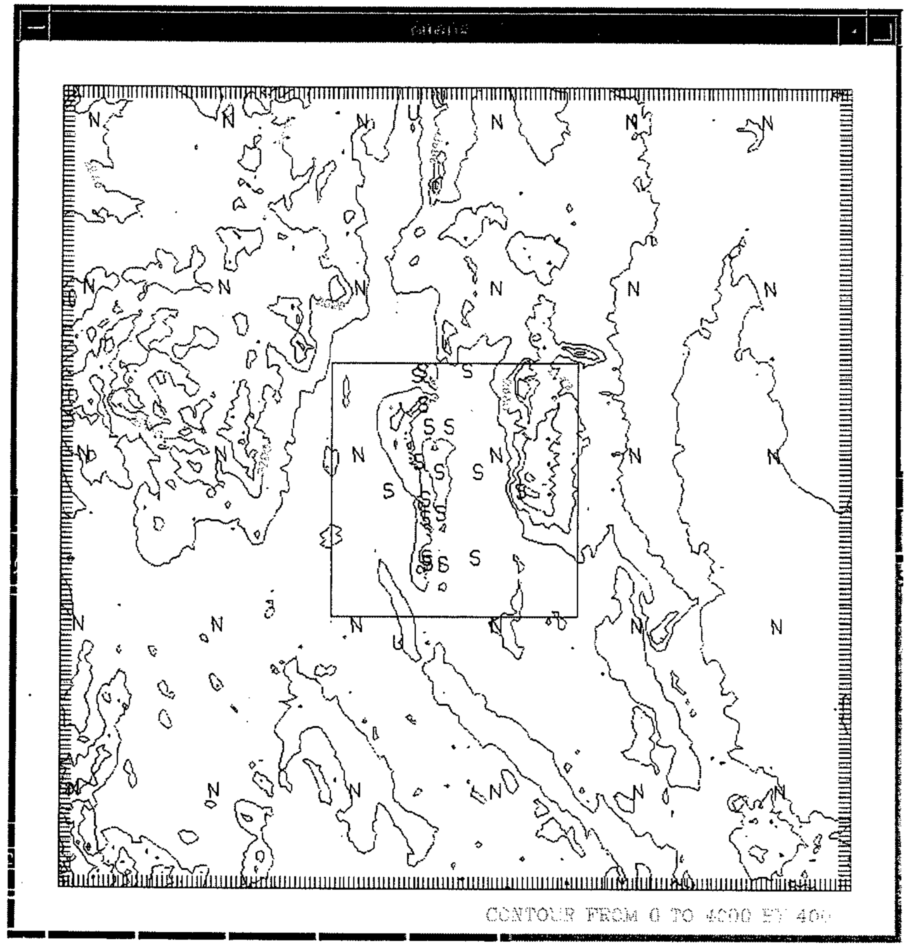
Note Stations in bold characters are used for the present comparison studies.

3. BFM Data

BFM is applied to a domain similar to the MM5 grid 3 area. The BFM domain consists of 51 x 51 grid points with a grid spacing of 3.33 km; this means a total model area of 166.7 x 166.7 km. The model vertical depth was set to 7 km above the highest elevation point in the domain and includes 16 layers. Forecast calculations are made twice daily initialized at 00 and 12 UTC. Figure 2 shows terrain data for the area of 533.3 x 533.3 km which contains the model domain at the central area. Also shown are the locations of input data for initial and lateral boundary conditions. In the figure, N represents the location of the Naval Oceanographic Global Atmospheric Prediction System (NOGAPS) forecast data points. The data are given at every 1° in both latitudinal and longitudinal directions. U represents the radiosonde stations. The data obtained at El Paso (located at 31.90° N and 106.70° W), and Albuquerque (located at 35.05° N and 105.62° W) are used.

The NOGAPS data were obtained through the internet homepage of the Master Environmental Library (MEL) addressed at: http://www-mel.nrlmry.navy.mil/homepage.html Horizontal wind vector components, temperature, dew point temperature, and geopotential height at 13 different pressure levels (1000, 975, 925, 900, 850, 700, 500, 400, 300, 250, 200, 150, and 100 mb) are obtained for the forecast periods of 0, 6, 12, 18, and 24 h. These data are interpolated to the 161 x 161 grid with the grid spacing of 3.33 km at each pressure level for the above forecast periods. With the exception of the 0 hour data, the data is vertically interpolated from the pressure levels to the BFM's height levels to produce three-dimensional fields of the input data. At 0 hrs, the NOGAPS data and upper air sounding data are composited and interpolated to the BFM vertical levels. [2]

Figure 2. Contour plot of terrain data.



Note - For the area covering of 533.3 x 533.3 km, centered at 32.80° N and 106.30° W, BFM model domain is located in the central area. Also shown are the locations of input data for initial and lateral boundary conditions. N represents NOGAPS data point, U for upper air, and S for SAMS stations.

The BFM vertical coordinate z^* is defined as

$$z^* = \overline{H}\frac{z - z_g}{H - z_g} \tag{2}$$

where

z is the Cartesian vertical coordinate,

z_g the ground elevation,

$\overline{H}$ the material surface top of the model in the z^* coordinate, and H is the corresponding height in the z coordinate defined by H= $\overline{H}$ + $z_{g\,max}$. $z_{g\,max}$ is the maximum value of terrain elevation in the BFM model domain.

The data fields covering the 51 x 51 grid points are used for forecast calculation. Details of the data analysis is described in reference 2.

Forecast calculation of the BFM is done as follows.

- Suppose a forecast calculation is initialized at time t_0.
- Precalculation will start at time t_0 -3 hour, and for 3 hours from t_0-3 to t_0 to t_0 the model fields are dynamically adjusted to the initial fields by the nudging method.
- The hourly lateral boundary condition data between two different forecast periods are calculated by a linear interpolation method.
- From t time t to t + 1, the data for t + 1 hour are assimilated in for 1 hr, and this process is repeated for an entire forecast period. For the present study, surface data are not used for initialization.

After the forecast calculation is completed, the following bilinear interpolation is conducted to obtain the BFM data at the SAMS locations. Suppose a SAMS location (x', and y') is surrounded by 4 BFM grid points. An interpolated value y' of an arbitrary variable y' at (x', y') is calculated using a bilear interpolation method as

$$\varphi_1=\varphi(i,j)+ (x'-x)\cdot[\varphi(i+1,j)-\varphi(i,j)] \tag{3}$$

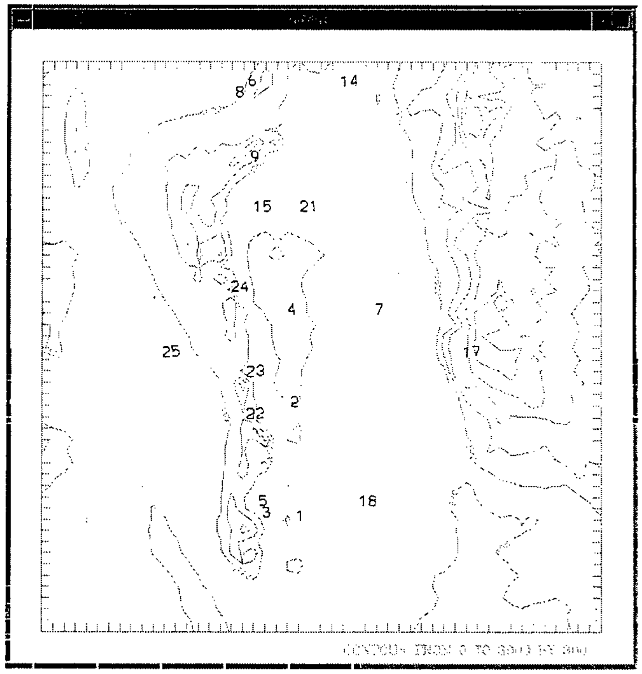
$$\varphi_2 =\varphi(i,j+1)+(x'-x)\cdot[\varphi(i+1,j+1)-\varphi(i,j+1)] \tag{4}$$

$$\varphi'(x',y') =\varphi_1 + (y'-y)\cdot[\varphi_2 - \varphi_1] \tag{5}$$

Here (i,j) is the southwest grid point of the 4 grid points surrounding a SAMS location (x',y'), and (x, y) is the distance location for the grid point (i,j); $\phi(i,j)$ is an arbitrary variable at (x,y). Figure 3 shows the terrain elevation data for BFM, covering the domain of 51 x 51 grid points with grid spacing of 3.33 km. In the figure, the locations of SAMS stations are represented by the station number listed in table 1. As can be seen in the figure, the majority of the SAMS are located in the central portion of the model domain and are not distributed evenly. Only a few stations are placed in the mountainous areas. Thus, the data set is, by no means,

ideal for mesoscale model evaluation. The results obtained in the present comparison study should be regarded as qualitative.

Figure 3. BFM model domain.



Note Covers the area of 51 x 51 grid points with grid spacing of 3.33 km, centered at 32.8° N and 106.3° W.

4 Statistical Parameters

The following statistical parameters between the forecast data, MM5 and BFM, and the observed SAMS data are calculated using the data for 42 days in the period between April 1 and May 31, 1999. Statistical parameters are calculated for temperature, relative humidity, wind speed and vector components at every forecast hour.

1. Mean Difference

$$MD = \frac{\sum_{j=1}^{m} \sum_{i=1}^{n} (x_{p,i,j} - x_{o,i,j})}{m \cdot n} \tag{6}$$

Here the subscripts $_o$ and $_p$ represent observation and prediction, respectively. The subscript $_i$ represents the i^{th} SAMS station, and the subscript $_j$ the j^{th} forecast day. n is the number of SAMS stations, and m the total number of forecast days. A nonzero mean difference (MD) indicates bias. For instance, if MD value is positive, it indicates that the model tends to over-forecast.

2. Mean Absolute Difference

$$AD = \frac{\sum_{j=1}^{m} \sum_{i=1}^{n} \left| x_{p,i,j} - x_{o,i,j} \right|}{m \cdot n} \tag{7}$$

3. Root mean square error (RMSE)

$$RMSE = \sqrt{\frac{\sum_{j=1}^{m}\sum_{i=1}^{n}(x_{o,i,j} - x_{p,i,j})^2}{m \cdot n}} \tag{8}$$

Good agreements between observation and forecast are, in general, related to smaller values of absolute difference (AD) and RMSE.

4. Root mean square vector error (RMSVE)

$$RMSVE = \sqrt{\frac{\sum_{i=1}^{m}\sum_{j=1}^{n}[(u_{o,i,j} - u_{p,i,j})^2 + (v_{o,i,j} - v_{p,i,j})^2]}{m \cdot n}} \tag{9}$$

This parameter measures the differences of both wind speed and direction. Again, good agreements of wind vectors are related to small values of the RMSVE.

5. Correlation Coefficient

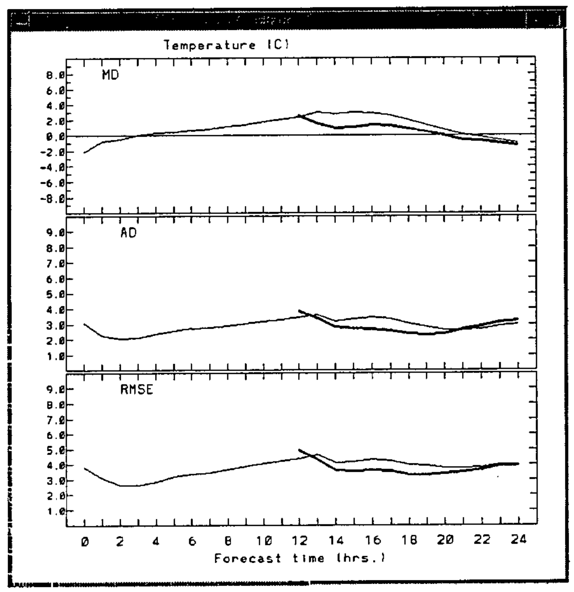
$$CC = \frac{\sum_{j=1}^{m}\sum_{i=1}^{n} y_{o,i,j} \cdot y_{p,i,j}}{\sqrt{\sum_{j=1}^{m}\sum_{i=1}^{n} y^2{}_{o,i,j} \cdot \sum_{j=1}^{m}\sum_{i=1}^{n} y^2{}_{p,i,j}}} \tag{10}$$

Here, $y_{o,i,j} = x_{o,i,j} - \overline{x_o}$, and $y_{p,i,j} = x_{p,i,j} - \overline{x_p}$. $\overline{x_o}$ and $\overline{x_p}$ are the means of observed and forecast values, respectively.

5. BFM Forecast and SAMS Data Comparison

As mentioned previously, the BFM forecast calculations are made twice daily initialized at 00 and 12 UTC. The purpose of this section is to compare forecast statistics of the two forecast calculations for the period of 12 and 24 UTC. Figure 4 through 7 shows the time series of the statistical parameters which are calculated every forecast hour. Forecast calculations initialized at 00 UTC are made for 24 h, and those initialized at 12 UTC for 12 h.

Figure 4. BFM and SAMS comparisons.



Note Time series of MD, AD, and RMSE for surface temperature (° C) are shown. Thin and thick lines represent forecast calculations initialized at, respectively, 00 and 12 UTC.

Figure 5. BFM and SAMS comparisons except for relative humidity (percent).

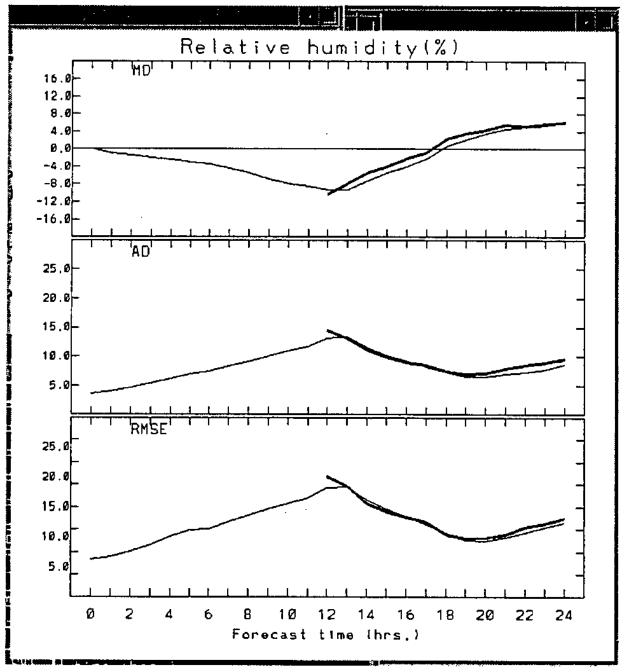


Figure 6. BFM and SAMS comparisons except for wind speed (m/sec).

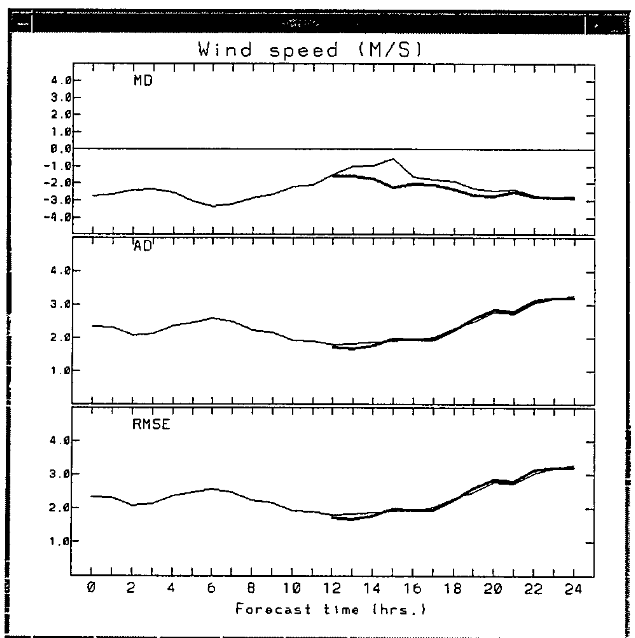
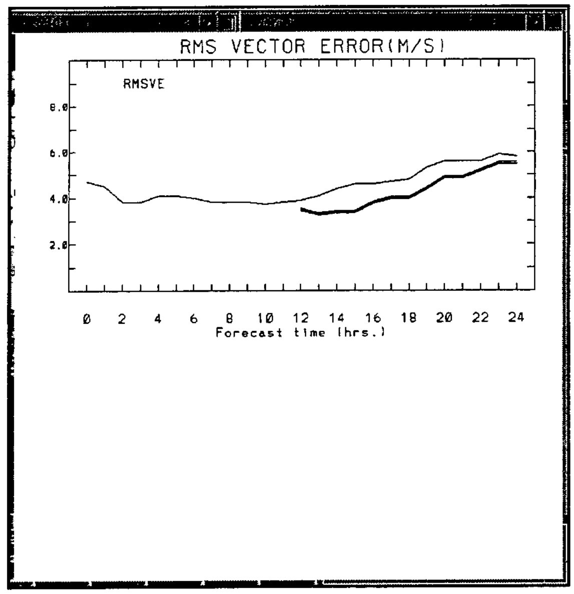


Figure 7. Time series of RMSVE (m/sec).



These figures show the following clearly :

- For temperature and wind speed and vector, the forecasts initialized at 12 UTC produce better results than those at 00 UTC for the same period of day. For relative humidity, the forecast calculations initialized at 12 UTC does not produce significant improvement over the ones at 00 UTC.

- The time series of MD for relative humidity initialized at 00 UTC shows that the BFM forecast tends to produce lower relative humidity than observation except for several hours of the local afternoon period.

- For temperature, the BFM tends to produce forecast values greater than observation for most of the forecast periods.

- For wind speed, the BFM tends to produce lighter wind speeds than those of observation.

- The time series of RMSVE shows that the forecast initialized at 12 UTC represents improved wind vector values over those initialized at 00 UTC for the same period of day.

Thus, it can be concluded for surface meteorological parameters over WSMR that the 12-h forecast calculation initialized at 12 UTC represents an improvement over the 24-h forecast calculation initialized at 00 UTC. This simply demonstrates that the BFM starts losing the forecasting skills with time.

6. Comparison of MM5 and BFM Forecast

As previously mentioned, the MM5 forecast data of surface parameters PSAMS are composed of two subsets of 12-h forecast calculation. Therefore, in the following, the corresponding data subsets of BFM are used for comparison.

6.1 Scatter Diagrams of Forecast Versus Observation

Figures 8a through 12b shows the scatter diagrams of forecast calculation versus observation. In these figures, *A* is for MM5 forecast, and *B* for BFM.

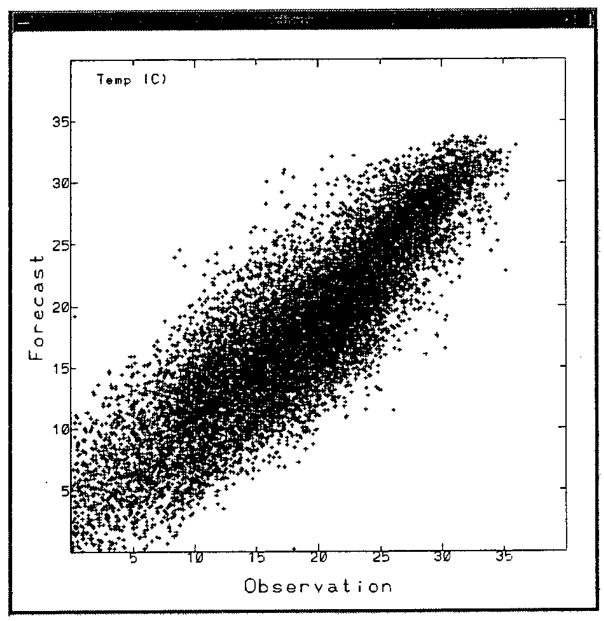


Figure 8a. Scatter diagram of MM5 vs. SAMS observation for temperature.

Figure 8b. Scatter diagram of BFM vs. SAMS observation for temperature.

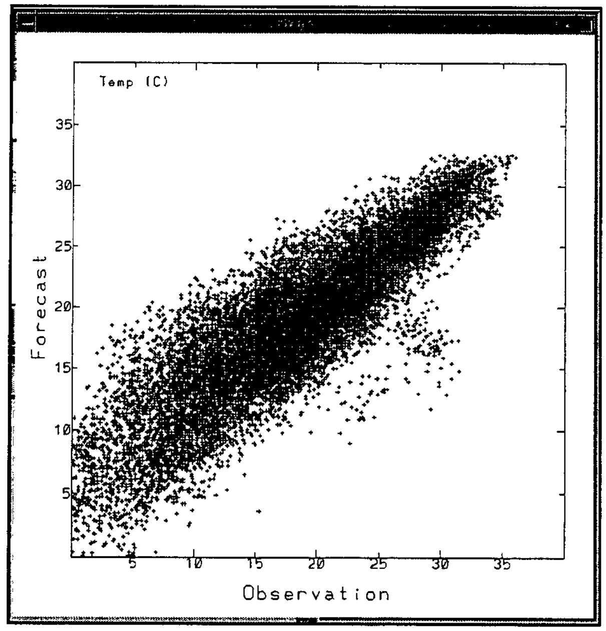


Figure 9a. Scatter diagram of MM5 vs. SAMS observation for relative humidity.

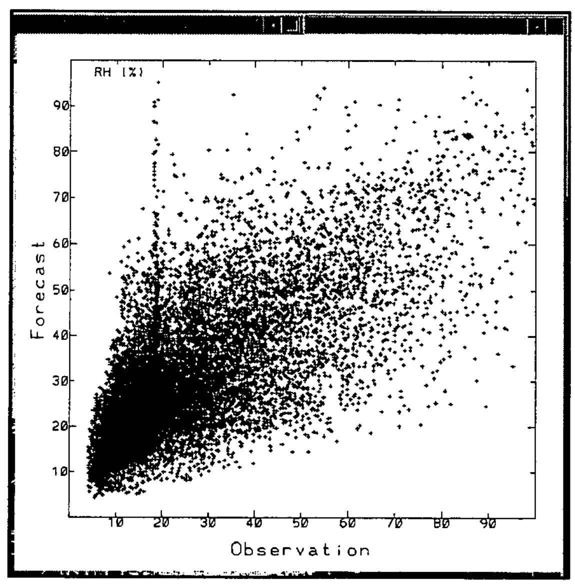


Figure 9b. Scatter diagram of BFM vs. SAMS observation for relative humidity.

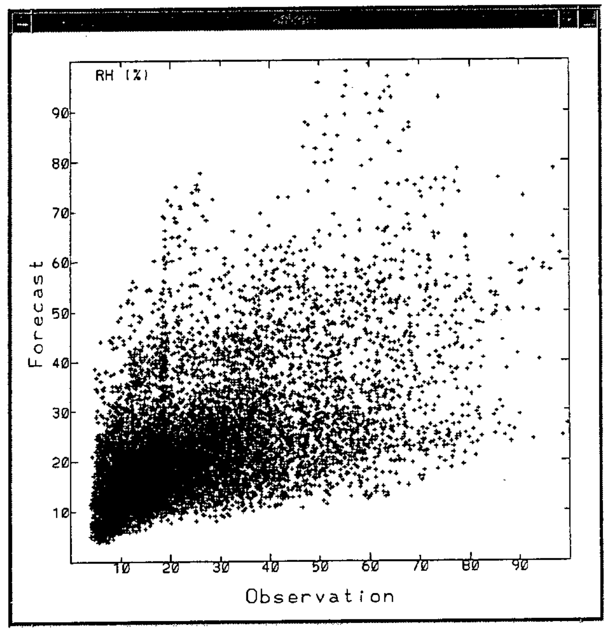


Figure 10a. Scatter diagram of MM5 forecast vs. SAMS for wind speed.

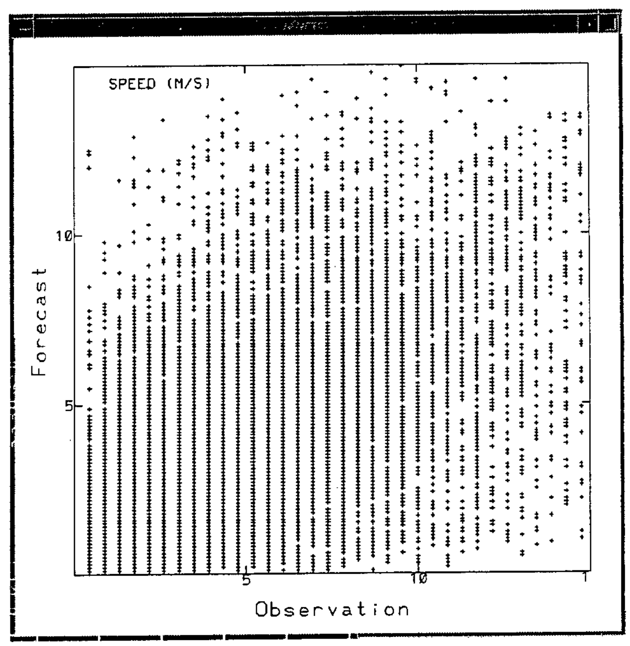


Figure 10b. Scatter diagram of BFM forecast vs. SAMS for wind speed.

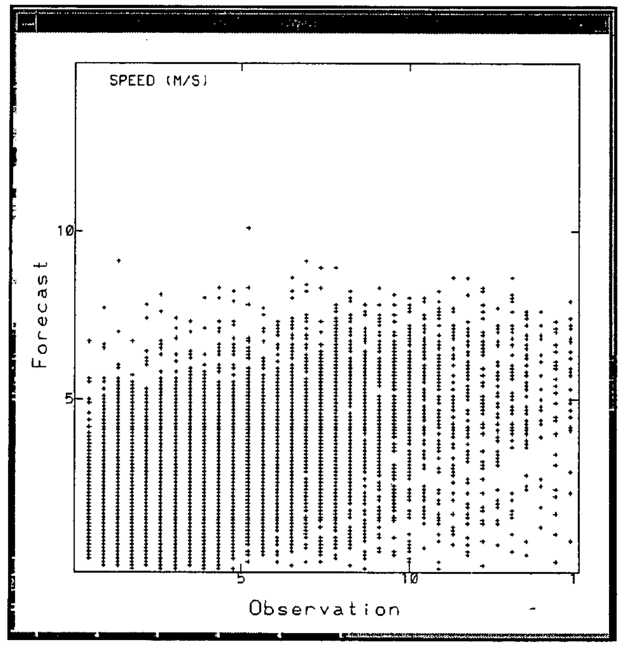


Figure 11a. Scatter diagram of MM5 forecast vs. SAMS observation for wind vector component, u.

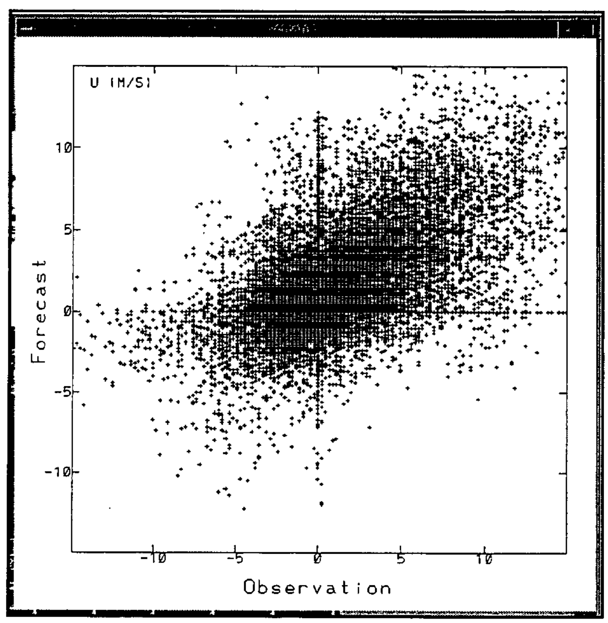


Figure 11b. Scatter diagram of BFM forecast vs. SAMS observation, for wind vector component, u.

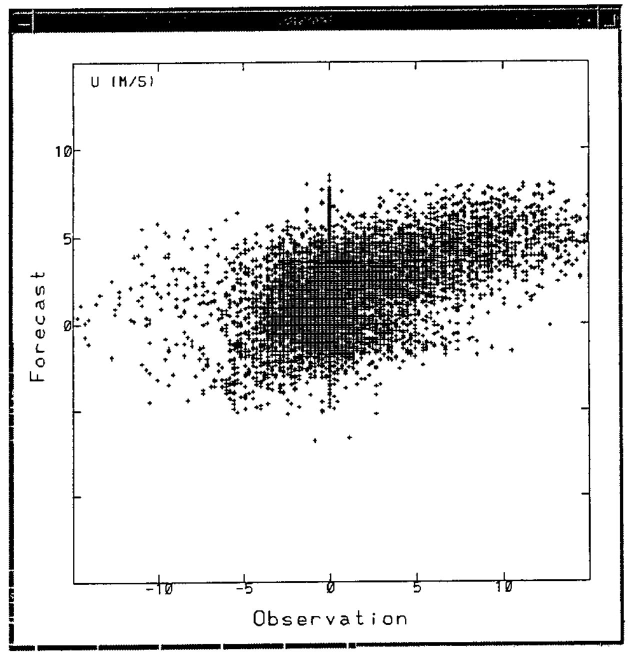


Figure 12a. Scatter diagram of MM5 forecast vs. SAMS observation, for wind vector component, v.

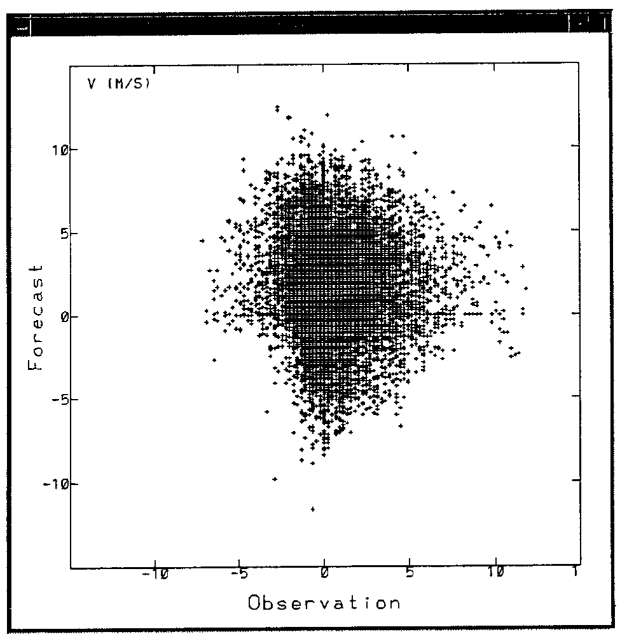
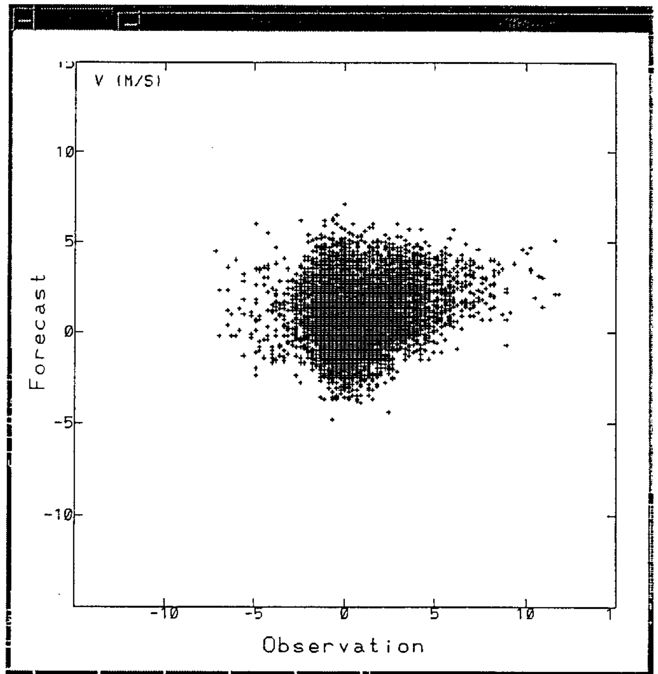


Figure 12b. Scatter diagram of BFM forecast vs. SAMS observation, for wind vector component v.



These scatter diagrams are composed of all the data points including 18 SAMS stations, for 24 h, and 42 forecast days. The correlation coefficients between the model forecast and the SAMS observation are calculated as appears in table 2.

Table 2. Correlation coefficients between forecast and observation

Parameter	MM5 vs. SAMS	BFM vs. SAMS
Temperature (C)	.88	.88
R.H. (%)	.72	.58
Wind speed (m/sec)	.38	.53
u (m/sec)	.44	.62
v (m/sec)	.004	.15

The following trends in the data can be seen.

- From figures 8A and B, there is good agreement for temperature between forecasts and observation for both MM5 and the BFM with the correlation coefficients 0.88.
- Reflecting dry atmospheric conditions over WSMR and the study period of April and May, 1999, data points of relative humidity are concentrated in lower left part of figures 9A and B. The figures show considerable scatter, indicating that both models have difficulties in simulating the moisture parameter near the ground surface. The correlation coefficient for MM5 forecast versus SAMS observations is 0.72, slightly the BFM's 0.58.
- For wind parameters, the correlation coefficients between BFM and SAMS are greater than those between MM5 and SAMS, but figure 10B clearly shows that BFM tends to under forecast the surface wind speed.

6.2 Station Statistics

The statistical parameters, MD, AD, RMSE, and RMSVE are also calculated for each SAMS station; these results appear in tables 3 through 6.

In tables 3 through 6, the statistical parameters calculated for MM5 are given in the left side of table and those for BFM are in the right side.

Table 3. Statistical parameters, MD, AD, and RMSE with statistics for MM5 and BFM.

Station Number	MM5			BFM		
	MD	AD	RMSE	MD	AD	RMSE
1	-1.0	2.4	3.0	-0.3	2.5	3.3
2	-0.5	2.6	3.3	0.3	2.6	3.5
3	-2.1	2.7	3.4	-1.0	2.5	3.2
4	0.6	2.8	3.3	1.5	2.8	3.9
5	1.5	2.7	3.3	2.4	3.3	4.0
6	-1.2	2.4	3.1	-0.2	1.9	2.4
7	1.0	2.8	3.7	1.2	3.2	4.3
8	-0.3	2.5	3.1	0.7	3.3	4.2
9	5.1	5.1	5.7	5.4	5.4	6.0
14	-0.4	2.3	3.0	0.7	3.0	3.8
15	-1.0	2.6	3.3	0.6	2.8	3.7
17	0.9	2.4	3.0	1.4	2.3	3.0
18	-1.8	2.4	2.9	-1.4	2.4	3.1
21	0.1	2.5	3.3	0.9	3.1	4.1
22	-1.0	2.0	2.5	-1.2	2.2	2.9
23	-2.3	2.7	3.4	-1.2	2.2	2.8
24	-4.7	4.8	5.4	-1.2	2.3	2.9
25	-0.8	2.2	2.8	0.5	2.7	3.4

Note Statistical parameters, MD, AD, and RMSE for temperature for each station. Statistics for MM5 are given in the left-hand side of table, and those for BFM in the right-hand side.

Table 4. Statistical parameters, MD, AD, and RMSE with statistics for MM5 and BFM except for relative humidity

Station #	MM5			BFM		
	MD	AD	RMSE	MD	AD	RMSE
1	4.4	7.8	10.1	-1.7	7.1	11.1
2	4.4	8.6	11.1	-2.1	8.1	12.1
3	6.4	9.6	11.9	-0.6	7.2	10.9
4	-0.4	10.2	13.6	-6.4	11.1	15.7
5	2.8	8.2	11.3	-3.7	8.5	13.4
6	6.1	9.8	12.5	0.6	7.6	10.4
7	2.1	9.4	11.9	-2.4	9.0	12.9
8	5.2	10.7	13.5	0.1	9.2	13.3
9	-0.7	9.8	14.1	-7.0	10.8	15.8
14	4.9	10.0	12.2	-0.3	8.9	12.6
15	4.5	9.2	11.7	-1.4	8.5	12.3
17	8.4	12.8	18.6	-0.1	9.9	15.2
18	6.7	9.7	12.0	0.1	7.6	11.3
21	3.7	9.8	12.3	-1.8	9.5	13.7
22	7.7	9.5	11.9	0.9	6.8	10.0
23	7.4	9.6	12.4	0.1	7.3	10.8
24	9.4	11.7	14.8	0.0	7.2	10.5
25	7.0	9.1	12.7	2.3	8.3	11.1

Note Statistical parameters, MD, AD, and RMSE for relative humidity for each station. Statistics for MM5 and are given in the left-hand side of table, and those for BFM in the right-hand side.

Table 5. Statistical parameters, MD, AD, and RMSE with statistics for MM5 and BFM except for wind speed

Station Number	MM5			BFM		
	MD	AD	RMSE	MD	AD	RMSE
1	-.9	2.0	2.6	-1.4	1.8	2.4
2	-1.5	2.4	3.1	-1.9	2.6	3.4
3	.1	2.2	3.0	-.3	2.1	2.7
4	-1.9	2.6	3.5	-2.7	3.1	3.9
5	-5.3	5.7	7.0	-5.9	6.2	7.8
6	-1.1	2.3	2.9	-1.9	2.2	2.9
7	-.8	1.8	2.3	-1.9	2.1	2.7
8	-1.2	1.9	2.5	-2.0	2.3	2.9
9	-2.7	3.5	4.6	-4.9	5.1	6.1
14	-1.4	2.1	2.6	-1.8	2.2	2.8
15	-1.1	2.0	2.7	-.8	1.9	2.5
17	2.2	2.7	3.3	-.6	1.6	2.0
18	-8	1.8	2.3	-2.2	2.5	3.1
21	-1.3	2.1	2.8	-1.8	2.1	2.8
22	-1.3	2.5	3.2	-2.0	2.7	3.5
23	-1.2	2.7	3.6	-1.8	2.9	3.9
24	.3	2.1	2.8	-.7	2.3	3.0
25	.6	1.4	1.8	-.3	1.0	1.4

Note Statistical parameters, MD, AD, and RMSE for wind speed for each station. Statistics for MM5 and are given in the left-hand side of table, and those for BFM in the right-hand side.

Table 6. RMSVE for individual stations for MM5 and BFM

Station #	MM5	BFM
1	4.3	3.8
2	5.5	4.6
3	4.5	4.2
4	4.8	4.1
5	8.5	9.5
6	5.7	4.5
7	4.2	3.2
8	4.7	3.6
9	5.5	5.2
14	3.8	3.0
15	3.9	3.6
17	5.0	3.7
18	4.4	4.0
21	4.2	3.4
22	4.6	4.2
23	5.1	4.7
24	4.7	4.0
25	4.2	2.5

Table 3 shows that both the MM5 and BFM had a difficult time with the temperature for station 9 (Salinas Peak). Both models consistently calculated the temperature warmer than observed values. The terrain elevation height for this station is 2,709 m (8941 ft) according to table 1. The height reduced from the terrain elevation data for BFM is 1,963 m, 746 m lower than the real height. The poor forecast of temperature for the station 9 by BFM may be caused by this discrepancy of height. For MM5, the terrain elevation data set is not available, but a similar reason may have applied to the poor forecasts. Otherwise, MM5 and BFM produced similar statistics for temperature.

For relative humidity (refer to table 4), the MM5 tends to forecast higher relative humidity than what is observed, while the BFM tends to forecast slightly lower than observation.

Table 5 and 6 show the statistics of wind speed and wind vector, respectively. It is noteworthy that both models produced lower statistical values for some stations located in mountainous site, # 5 (San Augustine Pass) and #9 (Salinas Peak) than other stations. In analysis of WSMR SAMS data using the data comprised of a 60-day period of March and April, 1990, Brock (1990) showed that #5 station has mountain peaks to the north and to the south so it rarely reports strong winds from the north or south and, instead, exhibits a wind rose showing predominantly east and west winds. The unit grid distance of 3.33 km used for both models may not be fine enough to resolve the local effect such as the above. [18]

According to table 5, both models tend to under-forecast wind speed, but the BFM under-forecasts wind speeds for all the stations more than MM5. In contrast, for RMSVE, the values for BFM are smaller for all the stations except #5 than those by MM5.

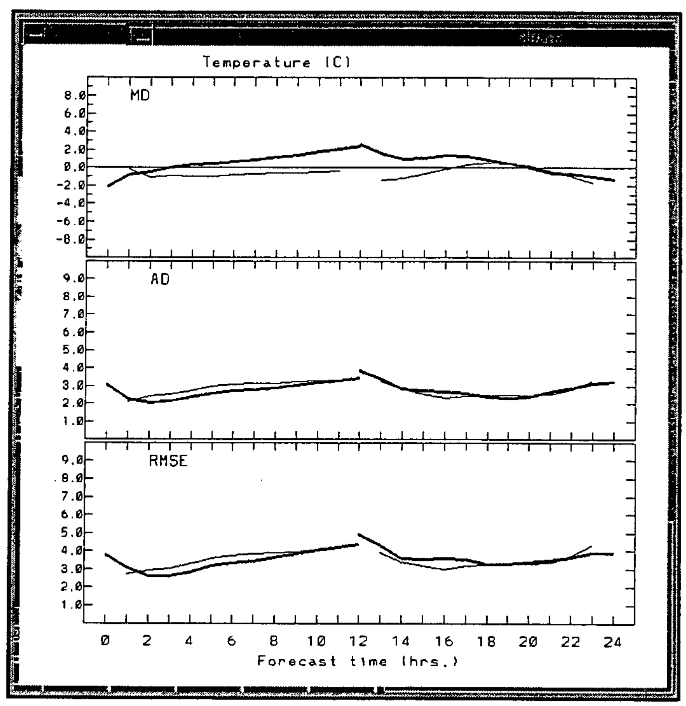


Figure 13. Time series of the statistical parameters, MD, AD, and RMSE for temperature. Thin and thick lines represent the MM5 and BFM, respectively.

Figure 14. Time series of the statistical parameters, MD, AD, and RMSE for relative humidity. Thin and thick lines represent the MM5 and BFM, respectively.

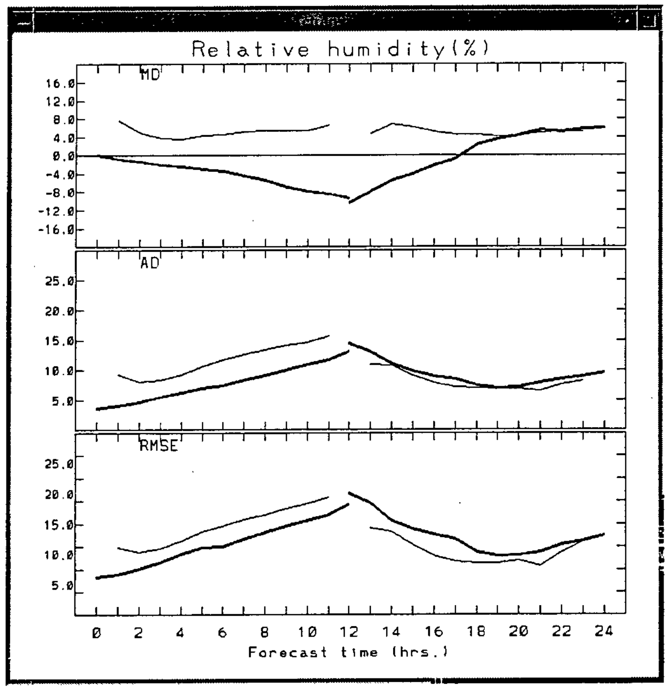


Figure 15. Time series of the statistical parameters, MD, AD, and RMSE for x-component of wind vector, u. Thin and thick lines represent the MM5 and BFM, respectively.

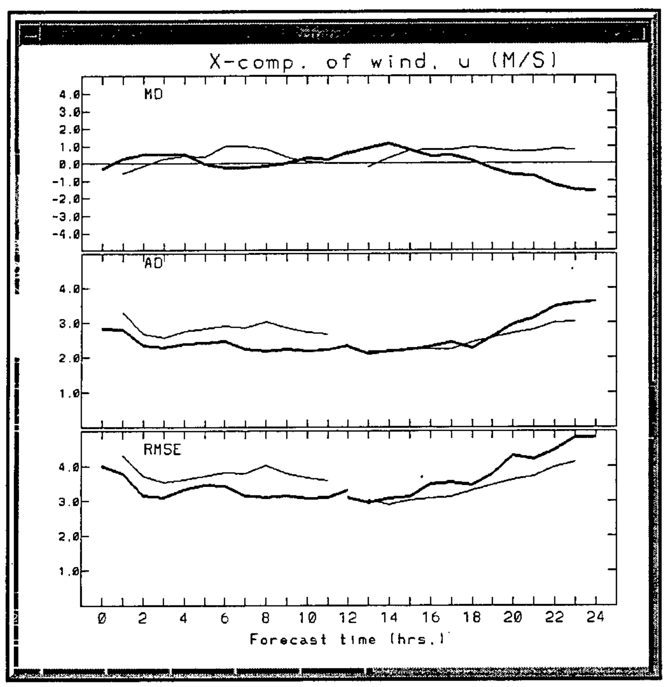


Figure 16. Time series of the statistical parameters, MD, AD, and RMSE for y-component of wind vector v. Thin and thick lines represent the MM5 and BFM, respectively.

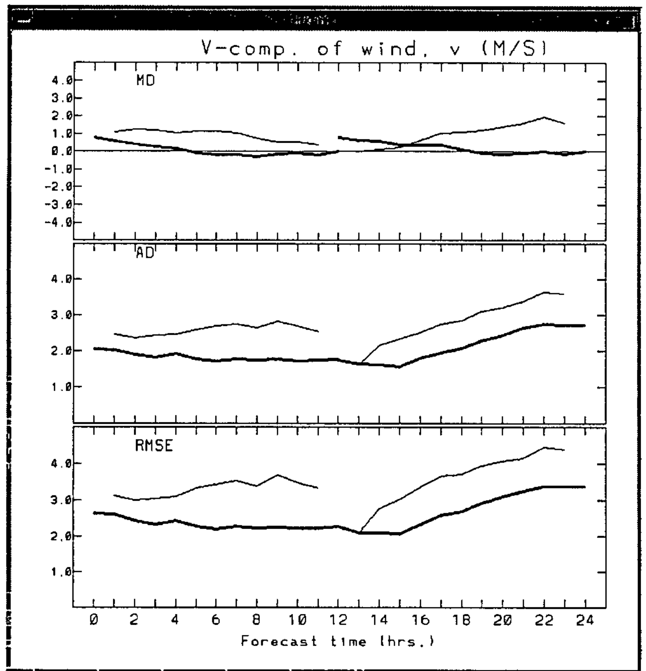


Figure 17. Time series of the statistical parameters, MD, AD, and RMSE for wind speed. Thin and thick lines represent the MM5 and BFM, respectively.

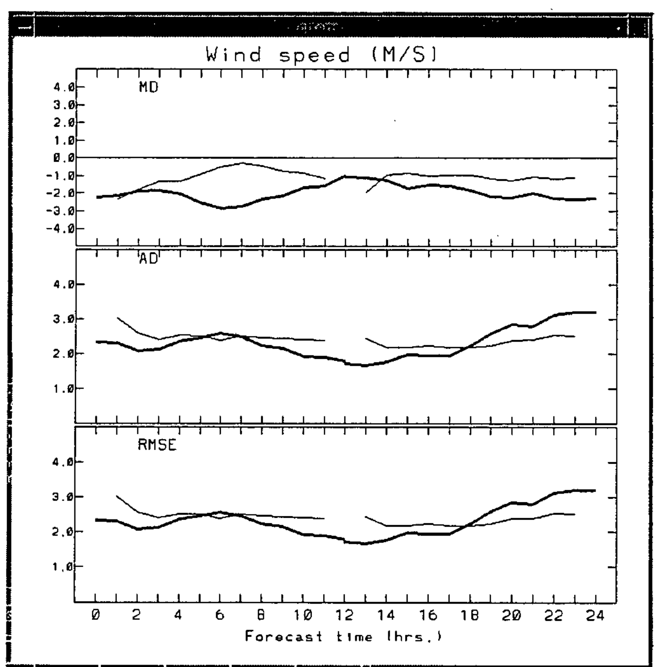
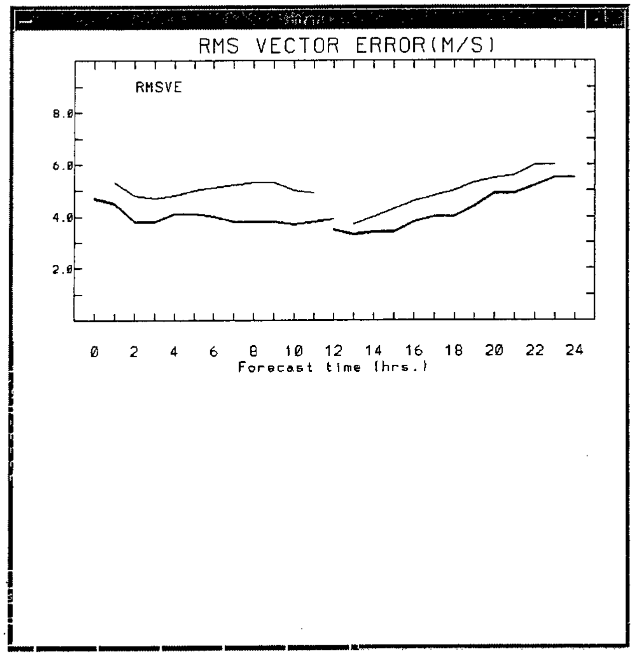


Figure 18. Time series of the RMSVE .



6.3 Time Series of Statistical Parameters

MD, AD, RMSE, and RMSVE are calculated every hour of the 24-h forecast period using 42 days of forecast data. For the MM5 forecast, PSAMS data files contain very few data at 00, 12, and 24 UTC. In figures 13 through 18, the values for MM5 are drawn with thin lines, and those for BFM with thick lines.

Inspection of these figures reveals that AD and RMSE vary proportionally. Therefore, in the following, AD is chosen for consideration. The following can be seen from these figures:.

- For surface temperature, the statistics of both models are very similar, except that MM5 under-forecasts temperature slightly, and that BFM over forecasts the temperature. Mean absolute differences for both models are about 3.0° C.

- MM5 forecasts produces a slightly higher relative humidity than observation throughout the 24-h forecast period. As shown in the previous section, the BFM tends to produce a lower relative humidity than observed from the evening to morning hours, and

from 00 to 12 UTC, the BFM produced smaller AD than MM5, and for the second 12-h period, both models produced similar AD values. The AD ranged within 15 percent.

- MD, AD, and RMSE of wind vector components u and v, and wind speed respectively in figures 15, 16, and 17, and the RMSVE in figure 18 show that both MM5 and BFM under-predicted wind speed throughout the entire forecast period. The under-prediction of wind speed is more significant for BFM than by the MM5. The RMSVE values of MM5 are greater than those of BFM throughout the 24-h forecast period. This is mainly due to larger errors of MM5 in calculation of the y-component of wind vector v.

- In a study of the BFM during June and July, 1998, over three different model domains (Colorado, Washington, and Florida) encompassing 500 x 500 km area with grid spacing of 10 km by Henmi (2000), the AD values for surface temperature are in the range of 2 to 3° C, which are similar to the AD values obtained by both MM5 and BFM in this study. However, for wind speed, the above study showed AD smaller than 1 m/sec, and RMSVE in the ranges of 2 to 3 m/sec for three different model domains. The present study shows that by the BFM AD values are in the range of 2 to 3 m/sec, and RMSVE in the range of 4 to 5 m/sec. In a BFM evaluation study over Colorado which covers a 500 x 500 km with a grid spacing of 10 km, D. Knapp and R. Dumais obtained the results of AD of 3.0° C for temperature and 1.8 m/sec for wind speed. Both results are similar to the results of the present study for temperature, but smaller for wind speed. At this point, it is not clear why both MM5 and BFM calculations over WSMR with a 3.33 km grid spacing have resulted in larger values of AD than in the previous studies. [19, 20]

6.4 Mean Wind Vector Fields

In figures 19, 20, and 21 (A and B), are mean wind vectors, respectively, at 00 and 12 local standard time (lst). The wind vectors calculated by MM5 are shown in figure 19, those by BFM in figure 20, and those observed in figure 21.

Figure 19a. Mean wind vectors calculated by MM5 for 00 lst.

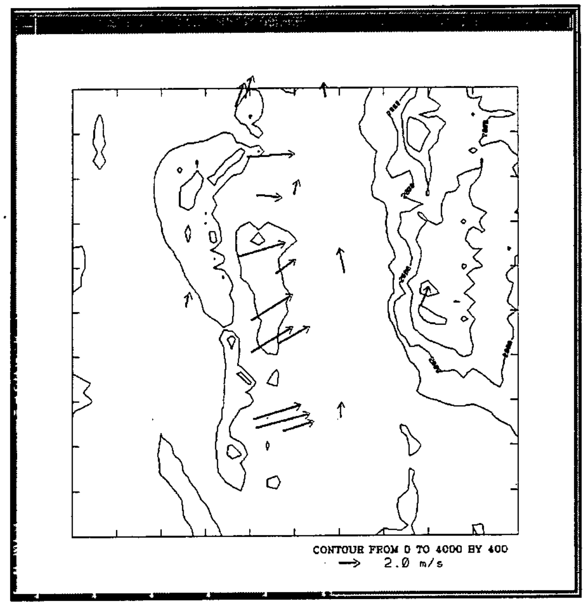


Figure 19b. Mean wind vectors calculated by MM5 for 12 lst.

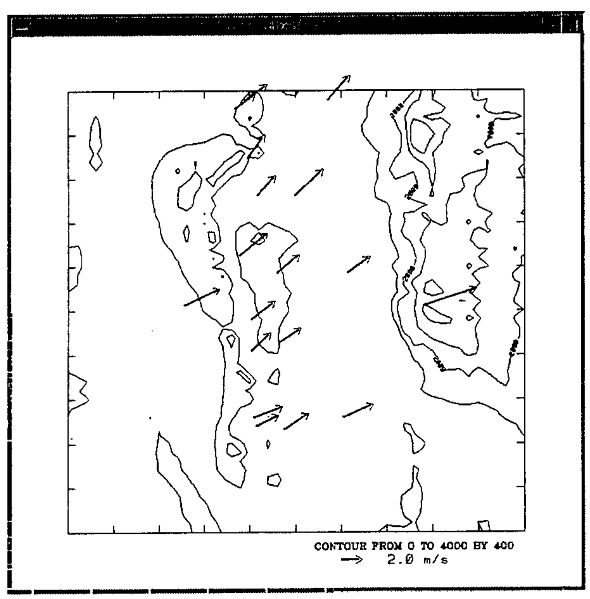


Figure 20a. Mean wind vectors calculated by BFM for 00 1st.

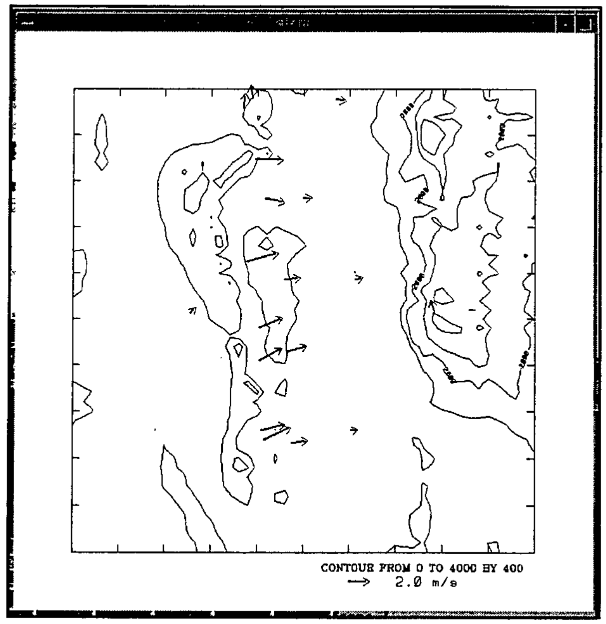


Figure 20b. Mean wind vectors calculated by BFM for 12 1st.

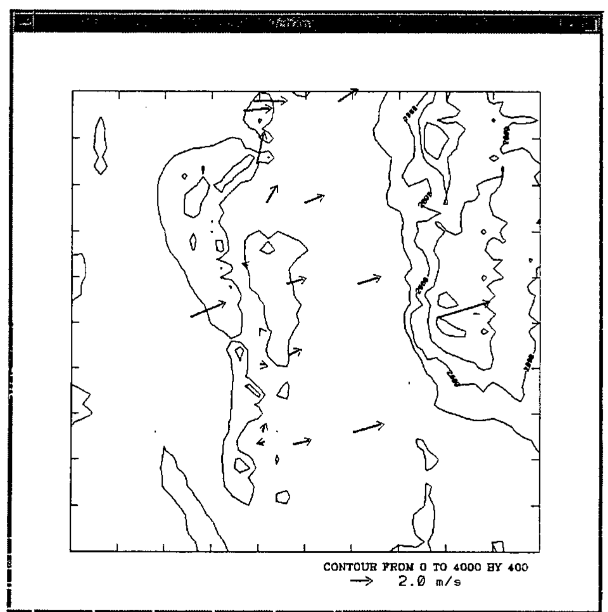


Figure 21a. Mean wind vectors by observation for 00 1st.

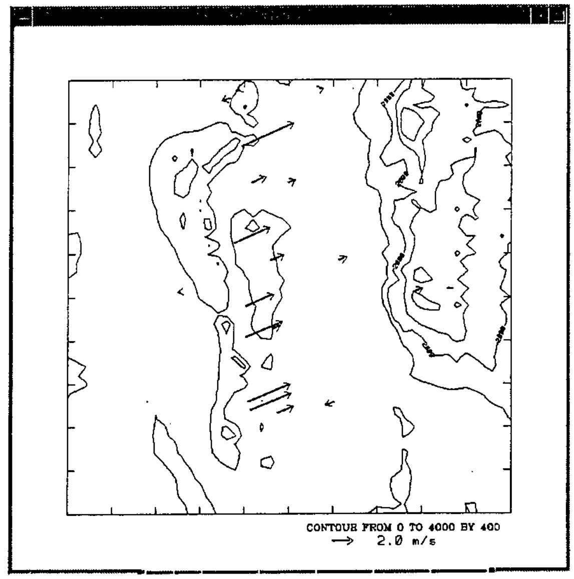
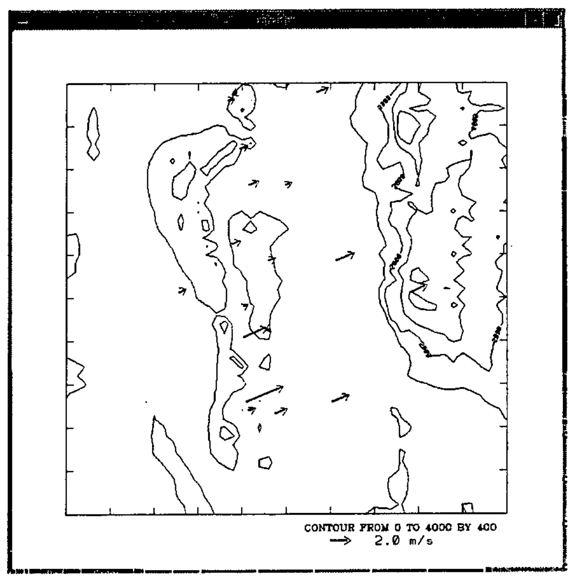


Figure 21b. Mean wind vectors by observation for 12 1st.



Both models were able to produce predominantly southwesterly flow patterns.

At 00 lst, the mean BFM wind vectors are more similar in direction to those observed; however, the BFM wind speeds are markedly less than the observations. On the whole, the MM5 wind speeds at 00 lst are closer to the observations.

At 12 lst, with the exception of two stations to the east of the Organ/San Andres mountain chain, observed wind speeds are quite light. The observed directions are all WSW. MM5 shows considerably higher wind speeds at this time than observed and shows a southwest wind direction for the more northerly stations. The BFM wind speeds appear to be intermediate between those observed and those given by MM5. In general, the BFM wind directions are quite similar to the observations.

7. Summary

MM5 and BFM forecast data over the WSMR covering the 42 days during April and May, 1999 are statistically compared with SAMS data. MM5 data interpolated to SAMS locations and archived on the computer of WSMR weather station are used for the study. Since the majority of archived daily data of MM5 are composed of two 12-h forecast data, the BFM calculations were correspondingly done twice a day, initialized at 00 and 12 UTC. Although forecast calculations initialized at both 00 and 12 UTC produced comparable results for the same period of day between 12 and 24 UTC, those initialized at 12 UTC produced slight improvement over those initialized at 00 UTC. The data for initialization and time-dependent boundary conditions were provided by the U.S. Navy's NOGAPS 0, 6, 12, 18, and 24-h forecast data, and upper-air sounding data at El Paso, Texas and Albuquerque, New Mexico.

The following results are obtained from the present study:

- From the scatter diagrams of forecast and observed data for all of the forecast days, it can be seen that the surface temperature forecast by both MM5 and BFM produced good agreement with SAMS data. On the other hand, both MM5 and BFM showed difficulty in forecasting the relative humidity at the surface. The scatter diagram of wind speed for BFM versus the observations shows that the model tends to under-forecast wind speed. The correlation coefficients for wind speed, and vector wind components (u and v) for both models are comparable, except that the correlation coefficient of v for MM5 is negative.

- The statistics at individual stations show that the temperature at station # 9 (Salinas Peak) was poorly forecast about 5° C higher than observation by both models. A major cause of this appears to be the large difference in elevation between the actual height and that effectively given by the models as their grid point data is interpolated to the station # 9 location. For wind speed and vector components, both models produced poor statistics for mountain stations #5 and 9, probably because the grid spacing of 3.33 km may not be fine enough to resolve local effects such as channeling and blocking effects of complex terrain.

- The 12-h forecast calculation by the BFM initialized at 12 UTC resulted in, for same time period of day, slight improvements over the 24 h forecast calculation initialized at 00 UTC.

- The time series of statistical parameters of both the MM5 and BFM for temperature are very similar, except that MM5 under forecasts and BFM over forecasts slightly. It may be concluded that both MM5 and BFM predicted the surface temperature fields over the WSMR model domain reasonably well. The BFM tended to produce a lower relative humidity than observed from the evening to the morning hours and slightly higher values in the afternoon; whereas, MM5 tended to produce a slightly higher relative humidity than observed throughout the 24-h forecast period.

- Wind speeds predicted by the BFM are less than those observed throughout the 24-h forecast period. However, probably due to poor performance of MM5 in simulating the y-component of wind vector, v, the RMSVEs for BFM are smaller than those for MM5 throughout the 24-h forecast period.

- The majority of SAMS stations in WSMR are located in the valley areas and are not distributed evenly in the model domain. Observed data at a few mountain stations are influenced by localized effects that could not be resolved by the grid spacing (3.33 km) used in the present study. Therefore, this study's statistics should be regarded as qualitative.

- Up to this time, the BFM has been mainly used with grid spacings greater than 5 km. This study is the first systematic attempt to use the terrain elevation data with grid spacing of 3.33 km. It is encouraging to see that a hydrostatic and a single-nested forecast model, the BFM, has produced comparable statistical results of surface meteorological parameters to the non-hydrostatic and triply-nested MM5.

- The present study was performed for the period of April and May, 1999 over WSMR. Further study is needed to cover different seasons and model domains, particularly the winter season in which synoptic scale weather patterns are important to local weather.

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Acronyms & Abbreviations

AD	absolute difference
AFWC	Air Force Weather Central
ARL	Army Research Laboratory
BFM	Battlescale Forecast Model
CAAM	Computer Assisted Artillery Meteorology
CSU	Colorado State University
FITNAH	numerical simulation model for flow over irregular terrain with natural and anthropogenic heat sources
GM	Global Spectral Model
HOTMAC	Higher Order Turbulence Model for Atmospheric Circulation
IMETS	Integrated Meteorological System
MD	mean difference
MM4	Fourth-Generation NCAR/Penn State mesoscale Model
MM5	Fifth-Generation NCAR/Penn State Mesoscale Model
NMC	National Meteorological Center
NCAR	National Center of Atmospheric Research
NCEP	National Center for Environmental Predictions
NOGAPS	Naval Oceanographic Global Atmospheric Prediction System
NORAPS6	Navy Operational Regional Prediction System Version 6
PSAMS	archived forecast data of MM5
RAMS	Regional Atmospheric Modeling System
RMSE	root mean square error
RMSVE	root mean square vector error

RWM	Relocatable Window Model
SAMS	Surface Atmosphere Measuring System
WIND	Nonuniform Domain
WSMR	While Sands Missile Range

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